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DEVELOPMENT OF A GENERAL HEARING CONSERVATION STANDARD FOR DIVING OPERATIONS: EXPERIMENT I COMPARISON OF TEMPORARY AUDITORY THRESHOLD SHIFTS INDUCED BY INTENSE TONE IN AIR AND WATER

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Development of a General Hearing Conservation Standard for Diving Operations:
Experiment I- Comparison of Temporary Auditory Threshold Shifts
Induced by Intense Tones in Air and Water

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Naval Submarine Medical Research Laboratory
Report 1203

Naval Medical Research and Development Command
Research Work Unit 63713N M0099.01C-5050

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A handwritten signature in black ink, appearing to read "R. G. Walter".

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Summary Page

The Problem

To develop a data base upon which to establish hearing-conservation standards for Navy divers exposed to waterborne noise.

The Findings

Bareheaded SCUBA divers may be exposed continuously for fifteen minutes to warble tones centered at 2000 Hz through 3000 Hz at sound pressure levels as high as 161 dB re 1 μ Pa, and to warble tones centered at 4000 Hz through 6000 Hz at sound pressure levels as high as 171 dB re 1 μ Pa without hazard to hearing. Bareheaded SCUBA divers may be exposed for four minutes to warble tones (125 Hz through 1000 Hz) at sound pressure levels as high as 161 dB re 1 μ Pa without hazard to hearing. Longer exposures at these frequencies and levels may not be innocuous. However, fifteen minute exposures to 500 and 1000 Hz warble tones are not hazardous to ears at 151 dB re 1 μ Pa. The warble tones used here are comparable to 1/3 octave bands of noise or frequency sweeps of the same extent (e.g. some sonar transmissions).

Application

These findings contribute to the establishment of a hearing-conservation standard for Navy divers exposed to intense noise in water.

ADMINISTRATIVE INFORMATION

This research was carried out under Naval Medical Research and Development Command Work Unit 63713N M0099.01C-5050, Development of a general hearing-conservation standard for diving operations. The views expressed in this report are those of the authors and do not reflect the official policy or position of the Department of the Navy, the Department of Defence, or the U.S. Government. It was approved for publication on 30 Sep 1996, and designated as NSMRL Report 1203.

Abstract

Preliminary hearing-conservation guidance for occupational exposure to intense waterborne sound has been developed but little supporting experimental evidence has been offered. This paper describes two attempts to experimentally determine the auditory hazard to SCUBA divers exposed to intense noise in water. Navy divers using US Navy approved self contained underwater breathing apparatus were exposed to waterborne warble tones with center frequencies of 125 Hz through 6000 Hz in two experiments. In the first experiment, the subjects, seven divers, were exposed continuously for 15 minutes to warble tones with center frequencies of 250 Hz through 6000 Hz both in air and in water and temporary auditory threshold shift measurements were taken. Maximum exposure levels in water were 141 dB re 1 μ Pa at 250 Hz, 161 dB at 500, 1,000, 2,000, and 3,000 Hz, and 171 dB at 4,000 and 6,000 Hz. Exposure levels of the warble tones in air were as high as 141 dB (115 dB re 20 μ Pa). A second group of 12 subjects were exposed continuously for four minutes to waterborne warble tones with center frequencies of 125 Hz through 6000 Hz at exposure levels of 121 to 161 dB re 1 μ Pa. For the first group (fifteen minute exposures) mean TTS was typically less than 5 dB following exposures in water regardless of exposure level except for the 500 Hz exposure condition. For the 500 Hz condition, TTS appeared to grow as a function of exposure level between exposure levels of 141 to 161 dB. The maximum TTS observed in any subject was 15.5 dB for any 15 minute exposure condition. For the second group, mean TTS was never as high as 10 dB for any exposure condition and no credible dose/response relationship was apparent. It was concluded that bareheaded SCUBA divers may be exposed continuously for fifteen minutes to warble tones centered at 2000 Hz through 3000 Hz at sound pressure levels as high as 161 dB re 1 μ Pa, and to warble tones centered at 4000 Hz through 6000 Hz at sound pressure levels as high as 171 dB re 1 μ Pa without hazard to hearing. Bareheaded SCUBA divers may be exposed for four minutes to warble tones (125 Hz through 1000 Hz) at sound pressure levels as high as 161 dB re 1 μ Pa without hazard to hearing. Longer exposures at these frequencies and levels may not be innocuous. However, fifteen minute exposures to 500 and 1000 Hz warble tones are not hazardous to ears at 151 dB re 1 μ Pa. The warble tones used here are comparable to 1/3 octave bands of noise or frequency sweeps of the same extent (e.g. some sonar transmissions). Because initial exposure levels were low, insufficient time was available to create conditions in which measurable TTS could be induced with most in-water exposures. Some results indicate that at 500 Hz, noise exposure levels in water may be about 25 dB higher than permissible exposure levels in air.

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Development of a general hearing conservation standard for diving operations:
Experiment I -Comparison of temporary auditory threshold shifts
induced by intense tone in air and water

Navy divers are exposed to intense water-borne noise originating from several sources including a variety of hand-held tools and large-scale active sonar systems undergoing in-port testing (Smith et al., 1970; Harris, 1971, 1973; Mittleman, 1976; Molvaer and Gjestland, 1981; Pearson, 1981; Smith, 1983, 1985). High-frequency sonar is also used as a means of acoustically tracking divers, resulting in additional noise exposure (Deatherage, et al., 1954; Mullen, 1966; Gill and Gardner, 1978; Rooney, 1979). Other noises reputed to bother divers include shipboard machinery noise radiated into the water through hulls, and noise produced by construction activity such as pile driving. In a study by Molvaer and Gjestland (1981), tools were found to produce A-weighted noise levels of 170.5 dB re 1 μPa^1 octave band levels produced by a commonly available underwater rock drill were found to be about 151 dB at 63 Hz, 145 dB at 125 Hz, 142 dB at 250 Hz, 140 dB at 500 Hz, and lower levels at higher frequencies. In the same study, another commercially available tool produced octave band levels 137 dB at 63 Hz, 140 dB at 125 Hz, 153 dB at 250 Hz, and about 163 dB at all higher octave bands. With few exceptions, the potential for these noises to damage divers' ears has not been assessed systematically. The present report describes an effort to develop permissible exposure limits (PELs) for underwater noise by comparing the amounts of temporary auditory threshold shift (TTS) induced by water-borne sound with TTS induced by airborne sound.

This is a continuation of previous work by Smith and Wojtowicz (1985) and Smith et al. (1988) using a paradigm developed by Smith et al. (1970).

Because there were few experimental data on the effects of intense waterborne noise on hearing (Montague and Strickland, 1961; Smith et al. 1970), Smith (1983) suggested that PELs for underwater noise be based upon the differences in hearing-threshold sound pressure levels (SPLs) in water (Smith, 1969, Brandt and Hollien, 1967) vs. in air (ISO, 1961). It was assumed that the dynamic range of the ear is the same in both media although the frequency responses differ. That is, regardless of whether the ear is immersed in air or in water, noises that are equally high above threshold level are equally hazardous. The only direct test of this procedure was a comparison of TTSs which were intentionally induced by controlled exposures to 3500 Hz tones in air and in water (Smith et al., 1970). While those single-frequency TTS results agreed well with the prediction of the hazard based upon the equal sensory magnitude assumption (Smith, 1983), subsequent results at other frequencies were not predicted well (Smith and Wojtowicz, 1984; Smith et al., 1988). The latter authors suggested that among possible causes of the failure could be that, as Montague and Strickland (1961) found, the dynamic range of the water-immersed ear is smaller than for the ear in air, and/or the Brandt and Hollien (1967) data used as normative data for the equal magnitude procedure may be masked thresholds.

1 All sound levels are referenced to 1 μPa unless otherwise indicated. Subtract 26 dB to obtain sound levels referenced to 20 μPa .

Objectives

This report describes results of two TTS demonstrations that were performed at Roosevelt Roads Naval Station in Puerto Rico.

It was intended to obtain further data against which the equal sensory magnitude assumption could be tested. The protocol for this research proposed initial, frequency dependent exposure levels based upon Smith et al. (1988), a pilot experiment specifically done for purpose of establishing initial exposure levels for the present experiments. The proposed initial exposure intensities in water were:

146 dB re 1 μ Pa at frequencies of 1000 Hz and below,

156 dB re 1 μ Pa at frequencies of 2000, 3000 and 4000 Hz,

146 dB re 1 μ Pa at 6000 Hz.

The proposed experimental protocol was reviewed by two Navy in-house committees for the protection of human subjects. Although presented with the Smith et al. (1988) results, those committees dictated that we use exceedingly conservative initial exposure levels. Although this limits the conclusions, the results can be used to establish safe levels of sound exposure for further tests of underwater noise hazard.

Experiment 1

Method

Subjects. The subjects were seven male U.S. Navy Divers having no hearing loss greater than 20 dB at any frequency.

Dive Site. The experiment was performed in November of 1993 in a seawater-flooded permanent graving dock at Roosevelt Roads Naval Station. Figure 1 is a sketch of the set up. A small pontoon boat (A), tethered to the dry dock wall comprised the dive plat-

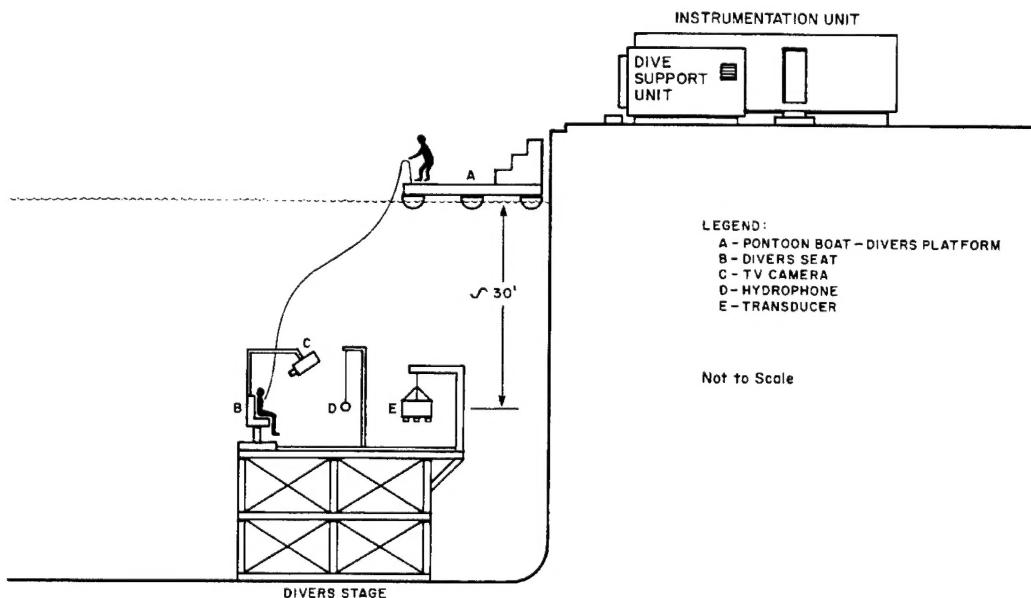


Figure 1. The experimental arrangement at Roosevelt Roads Naval Station.

form for the diving operations. The diver supervisor and the standby diver were stationed there. A fixed dive stage was mounted on the bottom of the dry dock (45 feet deep) and rose to a water depth of 30 feet. The dive stage held the sound sources on one end (E), the subject 12 feet from the sound source on the other end (B), and a monitoring hydrophone (D) half way between the sources and the subjects' position. At the subjects' position a B&K 8104 hydrophone used for calibration was suspended from a movable arm that could be rotated out of the way during exposures. It also served as an additional monitor hydrophone.

An underwater video camera, (C) - US Navy Diver Underwater Camera System, DUCS - was mounted on the stage to observe the subjects during exposures and to log events on video tape. A van located ten feet from the edge of the dry dock housed the diving support equipment including the DUCS console. Visual and verbal line-of-sight communications were maintained between the diver supervisor and the diver recorder stationed in the diver support van. The recorder continuously monitored the DUCS and maintained dive logs. A second, adjacent van (Instrumentation van) contained all sound generation and measurement equipment, as well as the auditory test equipment. Line of sight visual and verbal communications between the experimenters and the diver supervisor were maintained through a small port hole in the instrumentation van. Communications between the diver supervisor and the diver subject were by hand line through the diver tender. The subject could also be hailed by voice through the underwater loudspeaker of a diver communication system.

Sound Field. Warble tone waveforms were computed by a desktop microcomputer (Compuadd 325), downloaded to a programmable signal source (Tucker-Davis-Technolo-

gies), and passed to an Instruments Incorporated L-6 amplifier which drove one of two underwater sound projectors. Exposure frequencies were 250, 500, 1,000, 2,000, 3,000, 4,000, and 6,000 Hz. Warble tones (+/-5% of center frequency, 5 Hz warble rate) were used as stimuli to ameliorate the effects of standing waves within the test area. For frequencies of 1000 Hz and higher, the projector was a Underwater Sound Reference Detachment (USRD) F 56 transducer; lower frequencies were projected by a Honeywell HX-180 transducer.

The specific subject location for the exposures was determined prior to the experiment by mapping sound fields at various locations using a Brüel and Kjaer (B&K) 8104 hydrophone and a B&K 2133 real-time frequency analyzer. The maps were developed by recording the sound pressure levels at 1/2 meter intervals vertically and horizontally within a one meter cubic space. Several depths and standoff distances from the dry-dock wall were examined. The location with the least SPL deviation within a cubic meter was chosen for the exposure area. The subject exposure location finally chosen was about 24 feet from the graving dock wall with the subject facing the wall and the sound source between the subject and the wall. The best depth was about 30 feet.

Experimental Procedure. Prior to each exposure condition, the signal was projected and measured at the subjects' position (subject absent) with the B&K 8104 hydrophone and a B&K 2133 analyzer. The sound level at the second hydrophone (USRD F 42 D) that was located between the projector and the subjects' location was also recorded. This hydrophone was used to monitor the in-water stimulus level during exposures.

Each subject was administered a two-minute, single-frequency hearing test prior to

each exposure. The test frequency was 1/2 octave above the frequency to which the subject was about to be exposed. That is the frequency at which maximum TTS is expected to occur (Smith, 1984, 1988). Thus, for the exposure frequencies of 250, 500, 1,000, 2,000, 3,000, 4,000, and 6,000 Hz, the respective test frequencies were 375, 750, 1,500, 3,000, 4,000, 6,000, and 8,000 Hz. This test was administered to each subject's most sensitive ear at the frequency of interest (which may have differed left or right for each individual or individual exposure frequencies) based upon clinical and other prior audiograms. Although underwater sound would affect both ears, a single ear, the subject's most sensitive, was chosen for early detection of TTS. Effects in the contralateral ear were checked by comparing audiograms taken at the end of the day against audiograms taken the same morning.

Once the preexposure test was complete, the subject then entered the water, dove to the dive stage and signaled when ready. While remaining stationary, using open circuit SCUBA, the subject was to be exposed to a warble tone for 15 minutes.

At the conclusion of the noise exposure the subject had one minute to surface and exit the water. After examination by the diver supervisor, the subject was handed off to an audiometric technician. The subject and his tender arrived at the audiometric booth in the instrumentation van no later than two minutes after the end of the noise exposure. The subject's ears were examined by the audiometric technician and any excess water was removed by a swab if necessary. The subject then entered the booth and began the post-exposure hearing test at a frequency one half octave above the exposure frequency. It was planned to have the subject in the booth undergoing the post exposure test in time to measure TTS at four minutes after the end of the exposure.

Throughout this post-exposure test the subject was under observation by his tender through a window in the booth wall.

Some subjects experienced non-auditory sensations during exposure to 250 Hz. Because there was great interest in such effects, the subjects were subsequently instructed to surface when non-auditory effects were noted even if the effects were not disturbing. Consequently, especially at 1000 Hz, the exposure durations were less than 15 minutes for some of the upper exposure levels. Although the post exposure audiometric test was administered, those results are not included in further analyses of auditory effects.

Diving, In-water Exposure Regimen, and Termination Criteria. The experimental regimen consisted of up to seven repetitive compressed air open circuit SCUBA dives each dive day. The same exposure frequency was used throughout each day. During each dive a fifteen minute noise exposure was administered except at 250 Hz. Because of signal strength limitations it became apparent that no TTS would be produced by fifteen minute exposures at 250 Hz (the subjects could barely hear the signal). Consequently, exposure duration was reduced to five minutes at 250 Hz, a time sufficient to obtain reliable information on non-auditory sensations). On successive dives, the exposure level was 10 dB higher than the previous exposure level if a subject's TTS was less than 10 dB. The research protocol specified that if a subject's TTS was greater than 10 dB but less than 15 dB, his subsequent exposure level would be increased by 5 dB. If a TTS of 15 dB or greater was achieved, the subject would discontinue exposures for the day. The exposure levels were to be increased until a criterion TTS of 15 dB or greater was induced by a single exposure. As will be seen, because initial exposure levels were so low, no confirmed TTS of 15 dB or greater was observed in any

subject during these exposures with the exception of the maximum exposure level administered to a few individuals at a few frequencies. Accordingly, there were no instances in which less than a 10 dB increase was made for a subsequent exposure in water.

In-air Exposure Regimen. A similar exposure routine was followed on non-dive days with exposures administered by TDH-39 earphone to a single ear. Except for that, instrumentation and procedures for the in-air exposures were the same as for the in-water exposures. The in-air system was calibrated using a B&K 4152 artificial ear. Separate instrumentation setups were used for the two conditions however. Either system could provide backup for the other.

Results from the First Experiment

Exposures in water. Table I summarizes the results of the in-water exposures for exposure frequencies of 500 through 6000 Hz. Because of the small numbers of subjects and the varying numbers across conditions, the median as well as the mean TTS four minutes after the end of the exposure are shown. Similarly, in addition to the standard deviation, the lowest and highest TTSs observed and the number of subjects are shown for each exposure condition. The frequencies at which TTS was measured were about one-half octave above the indicated exposure frequencies. All data in Table I are for fifteen minute exposures. Table II shows the results for the five minute exposures at 250 Hz.

The number of subjects in the various conditions shown in Tables I and II varied for several reasons. Seven subjects reported for the experiment. One was disqualified for participation in the 6000 Hz exposure conditions on the basis of preliminary audiometry. A second subject incurred a very large threshold shift from exposure in air to 3000 Hz at 141 dB (115 dB re 20 μ Pa). He was disqualified

from further participation in the experiment. He was held for follow up observation and until his hearing level had fully recovered. He did make a dive to observe non-auditory effects at 250 Hz at 141 dB. After completing 3000 and 6000 Hz exposures, one subject withdrew from the experiment for personal reasons. At 6000 and 4000 Hz, after three subjects had yielded insignificant TTSs at the lower levels, the initial exposure level for subsequent subjects was 141 dB. At 3000 Hz the series was terminated for three subjects by a power failure after completing four dives with a maximum exposure level of 141 dB. Another power outage similarly affected data collection at 2000 Hz. At 1000 Hz, power failures occurring during exposures caused some to be terminated prematurely. Three subjects were run at 171 dB but those exposures were aborted because all three subjects experienced non auditory effects. At 500 Hz three of four subjects run were exposed at 161 dB but one exposure was aborted by a power failure that also precluded running the fourth subject at 161 dB.

TTS was not expected at 250 Hz because of signal strength limitations. Hence, exposure durations were limited to five minutes, a time sufficient to demonstrate the innocuous nature of those exposure conditions from an auditory perspective and for the subjects to make observations of non-auditory effects. At 250 Hz, two additional subjects (participating Diving Medical Officers) and five regular subjects made observations of non-auditory effects, chiefly vibratory sensations that were of interest for other purposes. The results of those observations are described in greater detail by Steevens and Smith (1996). Smith (1988) also reported on non-auditory effects accompanying exposure to intense waterborne sound. TTS results for 250 Hz are shown in Table II. The maximum exposure level was 141 dB and maximum TTS produced in any

Table 1
Temporary Threshold Shifts (15 Minute Exposures). Roosevelt Roads, Puerto Rico, November 1993. In-Water Exposures.

Exposure Frequency	Exposure Level dB re 1 μ Pa	Mean	Standard Deviation	Median	Low	Range	n
500 Hz	121	2.2	3.8	1.9	-1.6	6.6	4
	131	2.5	4.0	3.1	-2.2	5.8	4
	141	0.1	3.1	0.1	-3.3	3.3	4
	151	6.5	3.7	6.3	2.3	11.0	4
	161	13.9	2.3	13.9	12.3	15.5	2
1000 Hz	121	-2.7	8.3	1.3	-15.0	2.3	4
	131	0.7	1.8	0.2	2.7	6.8	3
	141	1.7	6.3	3.4	-6.9	6.8	4
	151	0.7	4.9	-0.3	-4.0	7.1	4
	161	6.2	6.5	7.5	-0.8	12.0	3
	171	1.7	1.4	2.4	0.1	2.6	3
2000 Hz	121	1.1	2.2	2.3	-2.3	2.7	5
	131	1.2	4.3	-1.3	-1.7	8.4	5
	141	2.2	6.1	0.2	-4.8	10.7	5
	151	0.9	4.1	0.9	-2.0	3.8	2
	161	0.4	2.8	0.4	-1.6	2.3	2
3000 Hz	111	0.1	6.1	-0.4	-9.5	7.0	6
	121	-1.5	7.3	-1.3	-10.3	9.9	6
	131	1.0	8.4	1.4	-9.9	10.7	6
	141	1.8	5.0	1.6	-3.8	9.7	6
	151	-2.6	9.2	-3.0	-11.6	6.7	3
	161	-1.5	9.5	1.3	-13.3	4.4	3
4000 Hz	121	0.4	1.0	0.8	-0.8	1.1	3
	131	2.2	5.0	-0.2	-1.1	8.0	3
	141	2.8	4.5	1.3	-1.3	9.3	5
	151	5.2	5.9	2.6	0.7	15.3	5
	161	1.3	6.6	-0.3	-5.7	10.4	5
	171	1.9	5.8	3.1	-6.7	9.1	5
6000 Hz	111	3.7	8.2	-0.6	-1.4	13.1	3
	121	-1.8	5.6	-1.6	-7.4	3.7	3
	131	-1.9	10.2	2.9	-13.6	5.1	3
	141	1.5	4.1	1.1	-2.7	8.4	6
	151	-0.4	5.0	-1.6	-5.5	6.4	6
	161	4.9	4.8	3.9	-1.2	12.7	6
	171	2.2	5.1	3.1	-4.3	7.3	6

subject was 4.8 dB. Median TTSs were -0.4 and 0.6 dB at 131 and 141 dB respectively.

In experiments involving diving, extraneous factors such as incomplete equalization of middle ear pressure following a dive can pro-

duce spurious threshold shifts. The ranges of TTS shown in Table I are the raw threshold changes existing at 4 minutes after the exposure terminated including suspected cases of spurious threshold shifts. The research protocol required that if a confirmed TTS of 10 dB

Table 2
*Temporary Threshold Shifts (5 Minute Exposures). Roosevelt Roads, Puerto Rico,
 November 1993. In-Water Exposures.*

Exposure Frequency	Exposure Level dB re 1 μ Pa	Mean	Standard Deviation	Median	Range	n	
					Low	High	
250 Hz	131	-0.9	4.2	-0.4	-7.7	4.8	7
	141	0.4	3.4	0.6	-4.8	4.2	7

was induced by any exposure, the subsequent exposure for that subject would increase by five rather than ten dB. Table I reveals a few instances in which that protocol rule was apparently violated. For example, one subject incurred a TTS of 10.7 dB when exposed in water to 3000 Hz at 131 dB. That subject's next exposure level should have been 136 dB. Yet, all six subjects were subsequently run at 141 dB. Two other instances are shown for exposure to 4000 Hz at 151 and 161 dB. In the first case, the TTS was initially recorded as 7 dB rather than 10.7 dB and that error was not detected until the data were reviewed later. In the other cases, the apparently significant TTSs were declared spurious by the first author. With the concurrence of the medical

officer and diving supervisor and the subjects, those subjects were subsequently exposed as if no significant TTS had occurred. The validity of those judgements was confirmed when the subjects involved incurred less TTS from subsequent exposures at higher levels. Other instances of apparent protocol violation may be seen in Table I.

At 111 dB and 121 dB at all frequencies all subjects reported the waterborne signals as barely audible. Only at the higher exposure levels did subjects report that the signal was louder than exhaust bubbles.

Figure 2 is a plot of the mean TTS for the in-water exposures for the exposure frequen-

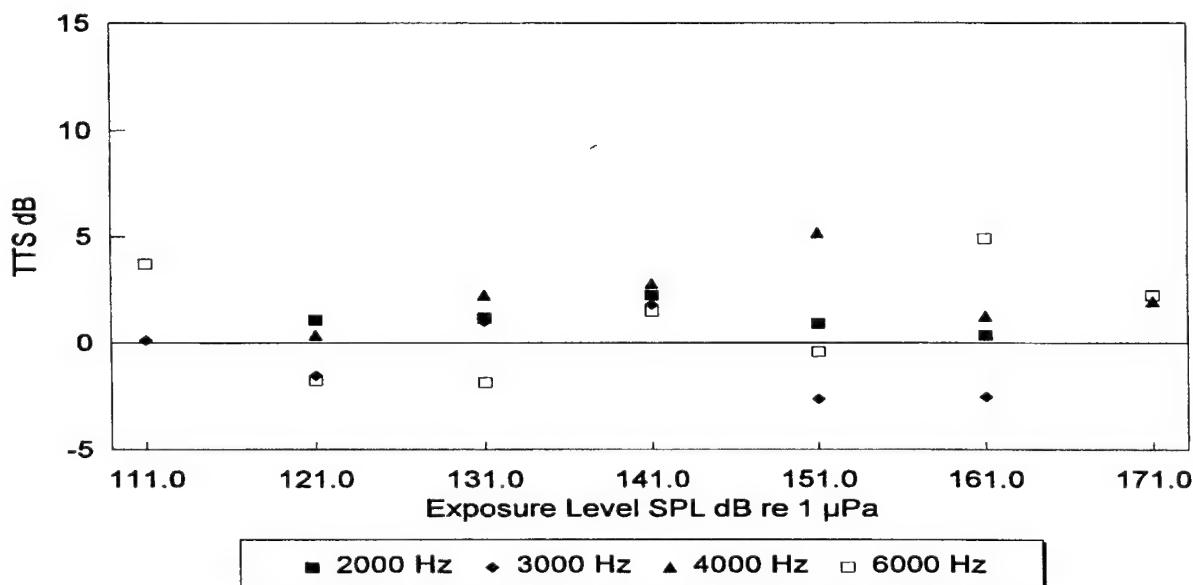


Figure 2. Mean temporary auditory-threshold shifts following fifteen-minute exposures in water to the exposure frequencies 2000 through 6000 Hz.

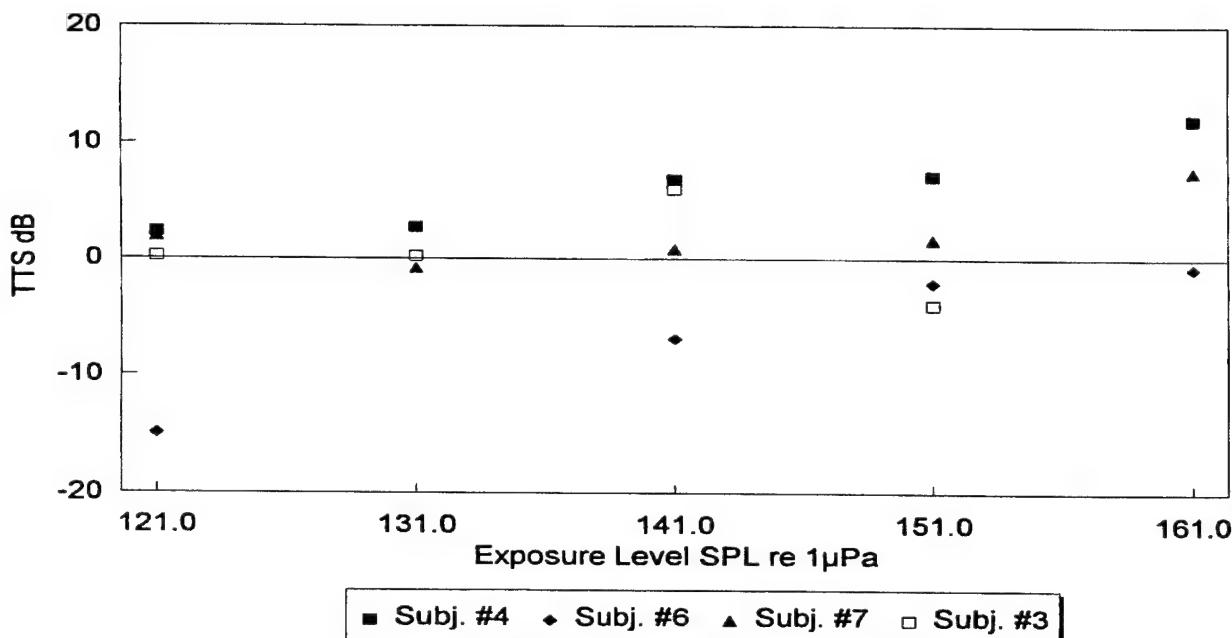


Figure 3. Individual subjects' temporary auditory-threshold shifts following fifteen-minute exposure to 1000 Hz warble tones in water.

cies 2000 through 6000 Hz. The number of subjects for each data point is shown in Table I. Note that there is a lack of clear dose-effect relationship even for exposure levels of 141 through 171 dB at 4000 and 6000 Hz. For those conditions, no subjects were eliminated

because of TTS as exposure levels increased. At 2000 and 3000 Hz there were only 2 and 3 subjects respectively for the 151 and 161 dB exposure conditions because of power failures. For the four frequencies in Figure 2, mean TTS never was as large as 5 dB. As

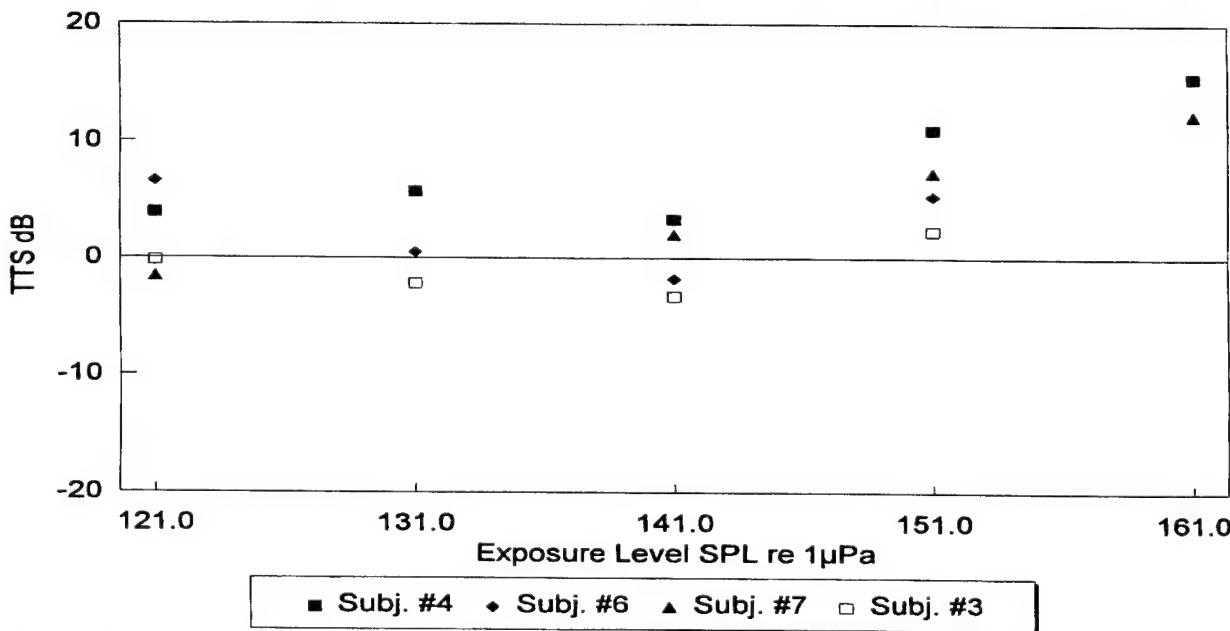


Figure 4. Individual subjects' temporary auditory-threshold shifts following fifteen minute exposure to 500 Hz warble tones in water.

shown in Table I, the maximum TTS observed at those frequencies, including suspected cases of spurious TTS, did not exceed 15.3 dB.

Figure 3 shows the individual results for four subjects at 1000 Hz. It suggests that median TTS becomes greater than 5 dB at the 161 dB exposure level although there is also suggested a growth of TTS beginning at lower exposure levels as well. Figure 4 is a plot of the individual results at 500 Hz for the same four subjects shown in Figure 3. It appears that onset of TTS may occur at the 151 dB exposure level at 500 Hz. At both 500 and 1000 Hz there was essentially no reliable TTS at exposure levels of 141 dB and lower.

Exposures in air. Figure 5 and 6 are plots of the mean TTS produced by exposures in air. These are unremarkable; rather typical dose/response relationships are evident at all frequencies. From the 111 to the 121 dB exposure levels, TTS increased between 5 and 10 dB depending on frequency. Both figures are less meaningful beyond 121 dB because

the number of subjects in each exposure level varied as some exceeded the 10 or 15 dB TTS limits. For the frequencies given in Figure 5, mean TTSs appear to be 10 dB or greater at the 131 dB level. Had all subjects been exposed at that level, the mean TTS, may have been higher. Exposures in air above 131 dB were not often administered at 2000 through 4000 Hz because subjects complained about the loudness of the signals. In general, the subjects found the exposures in air to be more unpleasant than the exposures they experienced in water. Some refused higher exposure levels after experiencing lower ones, others were not run at higher levels because the investigators believed sufficient data had been obtained for purposes of the research.

Pre-exposure audiograms. Although little TTS occurred for the in-water exposures, there is concern that the results, positive or negative, could result from changes in pre-exposure audiograms. If pre-exposure thresholds increased as a result of repetitive diving, effects of subsequent exposures could be masked. It is also possible that similar time-

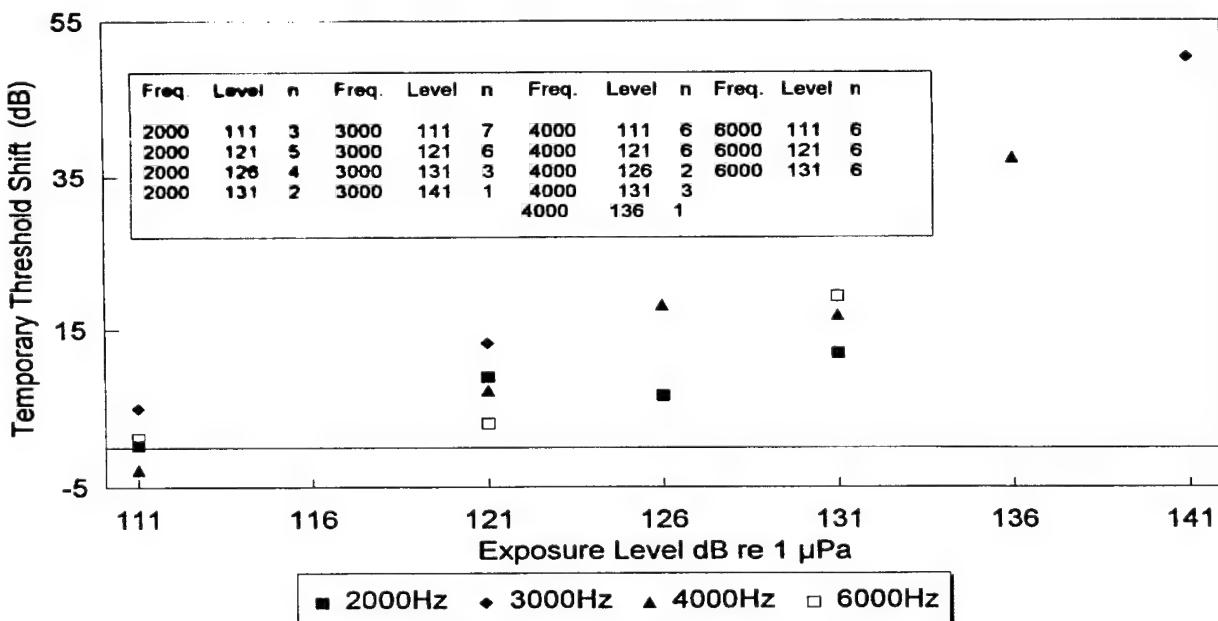


Figure 5. Mean temporary auditory-threshold shifts following fifteen-minute exposures in air to the exposure frequencies 2000 through 6000 Hz.

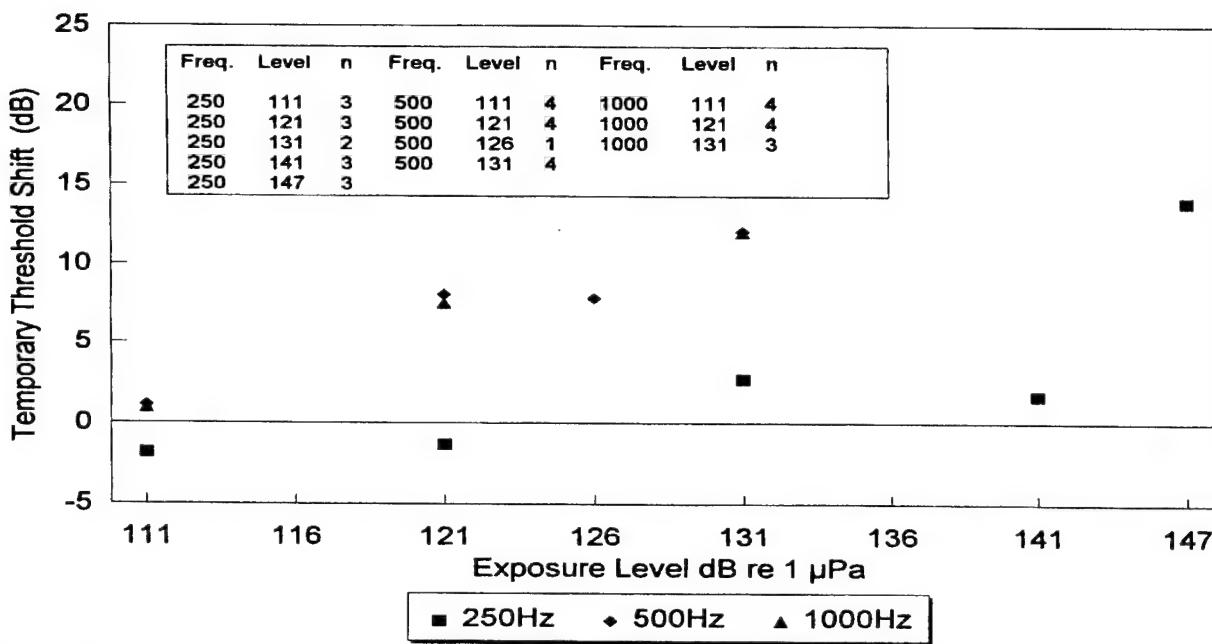


Figure 6. Mean temporary auditory-threshold shifts following fifteen-minute exposures in air to the exposure frequencies 250 through 1000 Hz.

order effects could have affected the data during the later stages of the experiment. The only frequencies at which potentially significant TTS was found were at 1000 and 500 Hz, the last two frequencies administered during the experiment.

Figure 7 presents plots for each test frequency (one half octave above the exposure frequencies) of the median pre-exposure thresholds across exposure episodes for in-air and in-water conditions. There are few indications of changes in pre-exposure thresholds that could bias the results significantly. At 4000 Hz (3000 Hz exposure frequency), the median pre-exposure threshold for exposure #6 is about 6 dB lower than that for exposure #5. This could have produced a larger apparent TTS at 161 dB than 151 dB. Table I does show that the median TTS ($n = 3$) did increase from -3.0 to 1.3 dB, a result explainable on the basis of the different pre-exposure baseline thresholds.

Daily audiograms. Figure 8 shows the results of daily audiograms taken each morning and each evening during the experiment and the differences between morning and evening audiograms. Only the data from the five men tested every day of the experiment are shown. Two subjects who did not complete the experiment are not shown. If alterations in hearing sensitivity affected the results it is probable that some indication would be seen in the audiometric data for 11-16 through 11-19. On the morning of 11-19, 500 Hz was not administered but it was in the evening. There was no diving on that date and only in-air, 1000 Hz exposures were administered. At 1000 Hz, median morning hearing levels were slightly lower (less than 5 dB) when that frequency was administered than earlier in the experiment. For the evening audiograms there was no apparent change in hearing levels at 1000 Hz throughout the experiment. The final panels of Figure 8 show the changes in hearing level from morning until evening. Negative numbers indicate improved hearing.

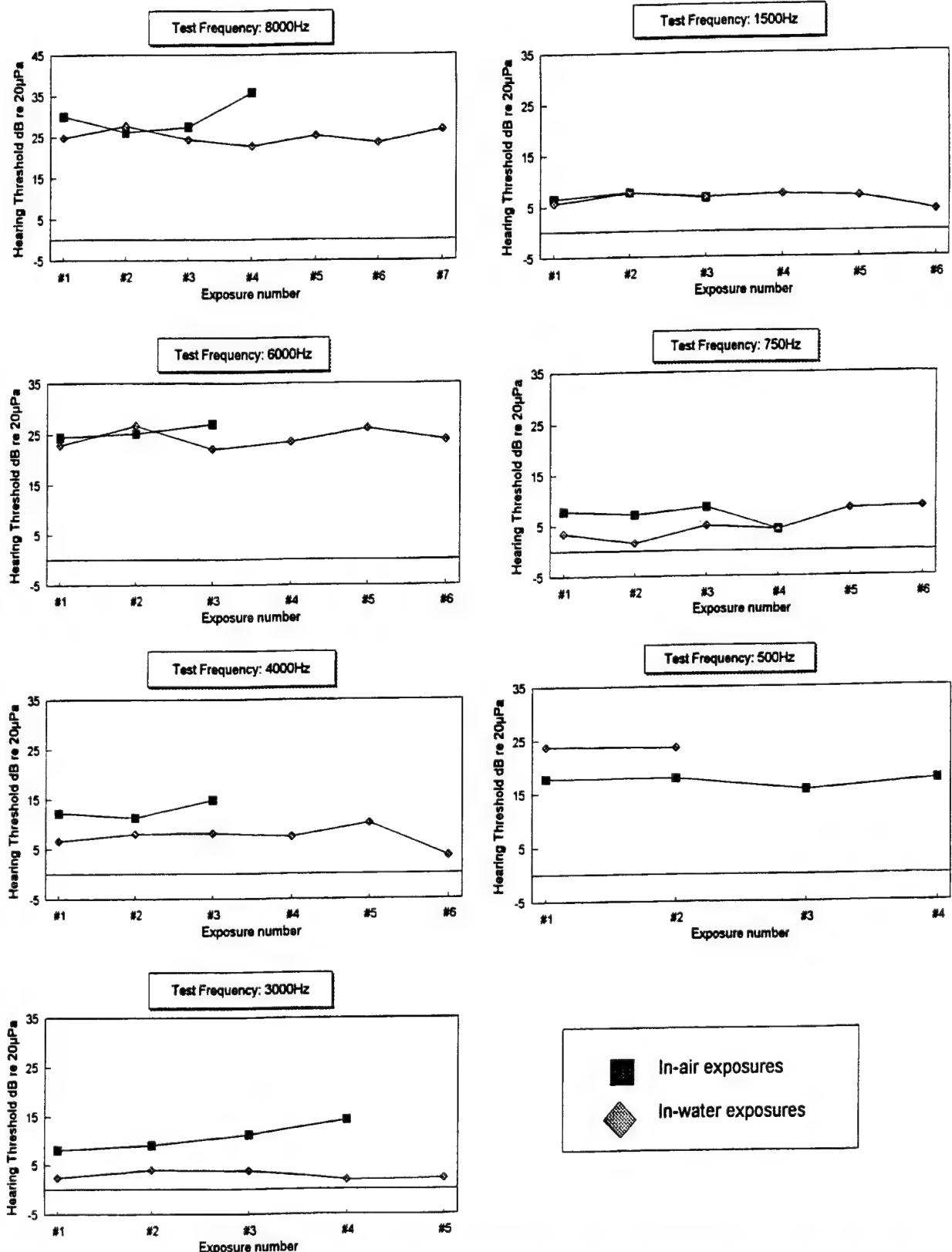


Figure 7. Pre-exposure threshold at temporary auditory-threshold shift test frequencies for the in-water and in-air exposures for the five subjects who completed the first experiment.

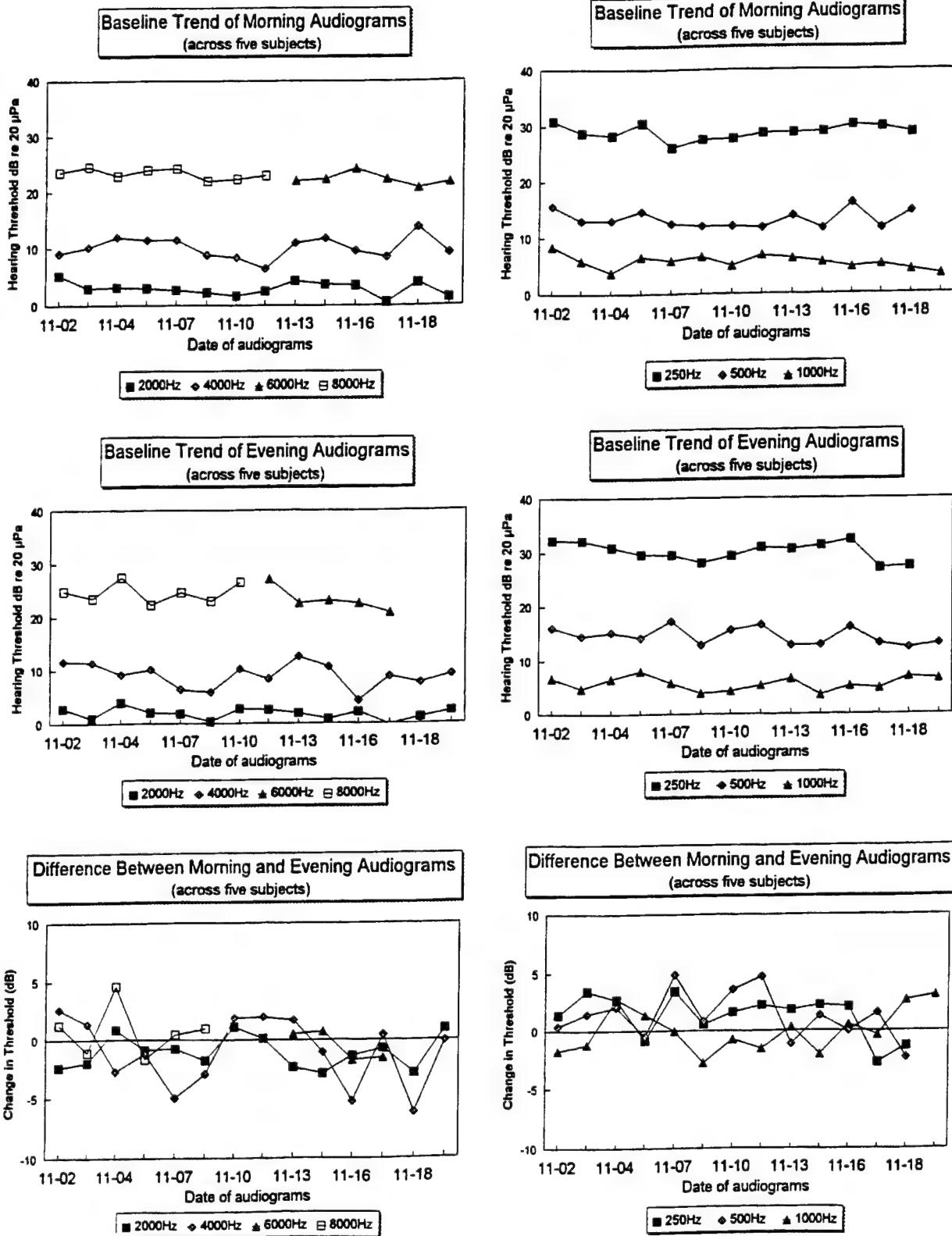


Figure 8. The results of daily audiograms (threshold sound pressure levels) taken each morning and each evening during the experiment and the differences between morning and evening audiograms by date of administration. Data are averaged over left and right ears for the five subjects who completed the first experiment. Negative numbers in the difference panels indicate poorer hearing (positive threshold shifts) in the evening than in the morning.

Little systematic change that could bias the results is evident.

Experiment 2

Following completion of the first experiment the results were presented and a second request was submitted to continue the experiment but to use the proposed initial exposure intensities in water. As stated in the introduction, these levels, based upon the results of Smith et al. (1988) were either 146 dB or 156 dB depending upon frequency. However, it was directed that the experiment continue using initial levels of 121 dB at all frequencies.

In order to maximize the efficiency of data collection, some changes to the protocol, all within the scope of the approved protocol, were made: The duration of exposures was reduced to four minutes and no exposures would be administered in air unless the corresponding conditions in water produced a measurable and reliable TTS.

Method

The methods was the same as for Experiment 1 except as follows:

Subjects. The subjects were twelve male U.S. Navy Divers having no hearing loss greater than 20 dB at any frequency.

Dive Site. This experiment was conducted at the same dive site as experiment 1.

Sound Field. For the second experiment, the low frequencies were projected by a USRD J 15-3 moving coil projector.

Experimental Procedure. During the second experiment the procedure differed from the first experiment in that a pre-exposure audiogram was not administered before each exposure. Rather, eight pre-exposure audiograms were given before any exposures began and before any diving was done. These

audiograms were averaged to determine a baseline pre-exposure threshold. All TTSs were computed from the average baseline thresholds.

Diving, In-water Exposure Regimen, and Termination Criteria. In the second experiment the exposure duration was four minutes and each day the exposure frequency was varied with exposure level kept constant. The exposure level was increased in the same manner as in the first dives, but on successive days instead of successive dives.

In-air Exposure Regimen. It was planned that no exposures in air would be administered except for experimental conditions producing reliable TTS from in-water exposures.

In addition to test frequency and order, exposure levels also differed in the two experiments. In the first experiment the desired exposure levels could not be achieved at the lower frequencies because of inadequate equipment. For example, the highest level attainable twelve feet from the source was 141 dB at 250 Hz. The HX-188 transducer was not useable at 125 Hz. In the second experiment a level of 161 dB was reached at both 125 and 250 Hz with a USRD J 15-3 transducer.

Results from the Second Experiment.

The method of computing TTS was altered in the second experiment. Instead of computing TTS against thresholds measured immediately prior to each exposure, a baseline was established in a series of tests prior to any noise exposures. The intent was to prevent possible diving-induced threshold shifts from contaminating the baseline threshold measurements. Also, to save time and increase the number of exposures possible within any one day, exposure durations were held to 4 minutes. On an equal energy basis, this is equiva-

Table 3a
Summary of temporary threshold shift results from waterborne exposure for Experiment 2

Exposure	121 dB			131 dB			141 dB			
	Level	Mean	S.D.	n	Mean	S.D.	n	Mean	S.D.	n
125	3.6	4.4		12	7.0	6.5	12	5.5	5.5	12
250	6.6	5.8		12	5.7	6.1	12	8.5	6.0	12
500	5.2	4.5		12	8.0	4.8	12	5.3	5.7	12
1000	-0.1	3.8		12	1.8	5.9	12	2.3	4.8	12
2000	0.9	3.5		12	1.7	4.5	12	4.8	4.2	12
3000	4.3	6.2		12	4.0	7.9	12	4.9	6.8	12
4000	4.6	7.89		12	6.2	7.7	12	6.5	5.8	12
6000	4.4	7.5		12	3.5	7.9	12	7.2	5.2	12

Table 3b
Summary of temporary threshold shift results from waterborne exposure for Experiment 2

Exposure	151 dB			161 dB			
	Level	Mean	S.D.	n	Mean	S.D.	n
125	5.6	6.1		12	5.9	5.9	9
250	8.6	8.1		12	6.8	7.2	10
500	5.5	5.7		12	5.1	2.7	10
1000	2.0	4.5		12	1.7	1.8	10
2000	2.5	6.5		12	0.9	2.1	10
3000	3.0	5.5		12	-0.2	1.8	10
4000	3.9	5.5		12	5.3	6.0	11
6000	4.6	5.7		12	5.5	6.8	12

lent to reducing each exposure level by 5.7 dB compared to the exposure levels used during the 15 minute exposures in the first experiment. There was a risk that any subclinical ear squeezes resulting from repetitive diving could produce apparent TTS as the day wore on. That would show up as spuriously large TTS at the lower exposure frequencies.

Table III is a summary of the results of the second experiment. It shows the mean TTSs,

standard deviations, and number of subjects for each exposure condition. Only 11 subjects are shown for the 151 dB exposure at 1000 Hz because the computer failed during one subject's post-exposure test after he had completed a four minute exposure. The reduced number of subjects at the 161 dB exposure levels is an artifact of the procedure. At the 161 dB exposure level, only 11 subjects were run at 4000 Hz because one subject incurred a squeeze following his first exposure

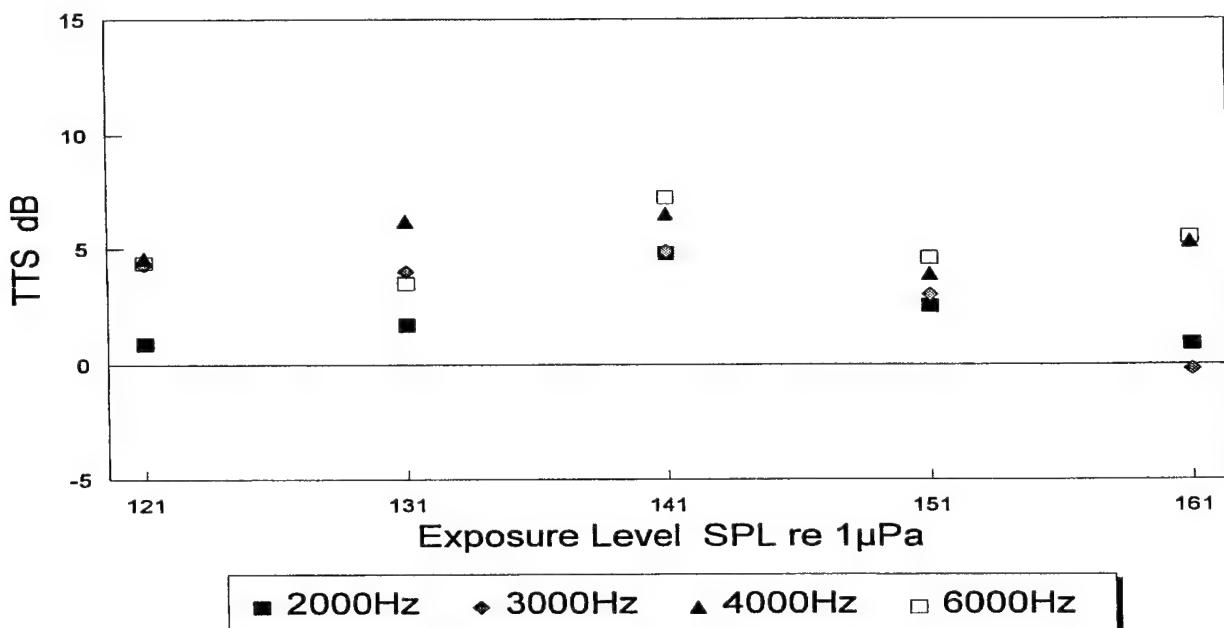


Figure 9. Mean temporary auditory-threshold shifts following four-minute exposures in water to the exposure frequencies 2000 through 6000 Hz.

and was disqualified from diving for the day by the on site Diving Medical Officer. Two subjects were subsequently eliminated because they incurred significant threshold shifts (not-necessarily noise-induced) at some frequencies. One incurred a TTS of 16.2 dB from the exposure at 4000 Hz. He was disqualified from exposure to any lower frequency by the attending medical officer. Thus for the sequentially presented frequencies of 3000 Hz through 250 Hz, there were only 10 subjects. Another subject incurred a 20.5 dB TTS at 250 Hz and was disqualified from participating at 125 Hz.

The mean TTS for exposure frequencies of 2000 through 6000 Hz is shown in Figure 9. Results for exposure frequencies 125 through 1000 Hz are shown in Figure 10. For these four-minute exposures mean TTS never exceeded 8.6 dB at any frequency or exposure level. As Figures 9 and 10 show, there was no credible dose/effect relationship at any frequency. However, as shown in Table III, subjects were eliminated for the 161 dB exposure level because they exhibited greater than 15

dB shifts at some point. The growth in TTS seen at 500 Hz for Experiment 1 (Figure 4) is not evident in Figure 10 but the exposure durations in the second experiment were shorter than the exposure durations in the first experiment, and the method of computing the base line differed from the first experiment.

Discussion

The results shown in Figure 2 for the fifteen minute exposures in water at exposure frequencies of 2000 through 6000 Hz show that mean TTS for those four frequencies never was as large as 5 dB even at exposure levels as high as 171 dB. At 4000 (n=5) and 6000 Hz (n=6) the number of subjects tested was sufficient that it is reasonable to conclude that at least half of any subjects exposed to these conditions would incur TTSs smaller than can be reliably detected in routine clinical audiology (5 dB). Contrast this with the results shown in Figure 5 for exposure in air at the same frequencies. It shows that by the 131 dB exposure level (100 dB re 20 μ Pa), most subjects had incurred at least a 10 dB TTS. Rough interpolation based upon the

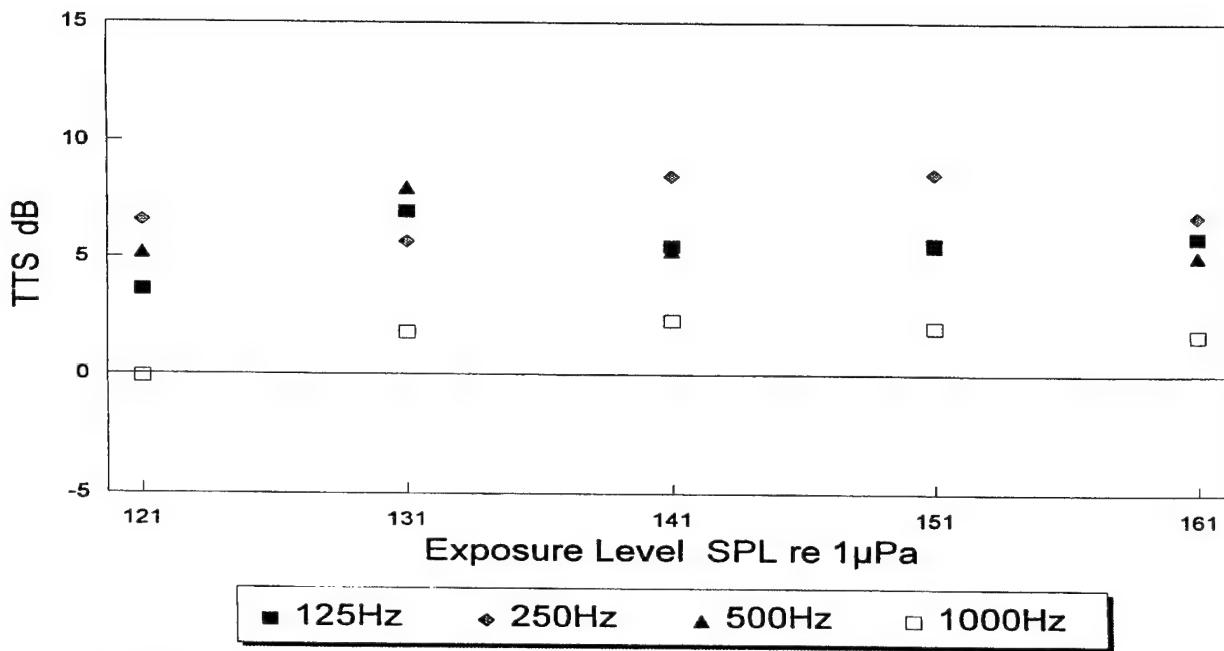


Figure 10. Mean temporary auditory-threshold shifts following four-minute exposures in water to the exposure frequencies 125 through 1000 Hz.

data points given in Figure 5 indicate that between the 118 dB and 124 dB exposure levels, the mean subject would have incurred a TTS of 10 dB at these frequencies. That is, the difference in TTS inducing potency for noise exposures in air and in water in this frequency region is at least 37 dB at 2000 and 3000 Hz and at least 47 dB at 4000 and 6000 Hz.

These results are not surprising. Smith et al. (1970) found that 15 minute exposures to 3500 Hz intermittent tones (1250 msec on, 1250 msec off) at 194 and 204 dB produced median TTSs of about 8 and 28 dB respectively ($n = 6$). Thus, even a continuous exposure for 15 minutes to tonal signals in the 3000 to 4000 Hz range at 171 dB would not be expected to produce measurable TTS in most subjects. Smith et al. (1988) found that a sound pressure level of 166 to 176 dB for tones at 1400 Hz produced about the same TTS as a 126 dB tone in air given the same exposure duration. Montague and Strickland (1961) found that divers would tolerate 1500 Hz tones at sound pressures up to 191 dB but not above 201 dB. That suggests that the

maximum level of 161 dB at 1000 and 2000 Hz that was used in the Experiment 1 would not produce much TTS.

The results for 15-minute exposure to 500 Hz indicate that at that frequency the mean subject would incur a 10 dB TTS with an in-air exposure level of about 126 dB. That magnitude of TTS would be induced by an in-water exposure level somewhat above 151 dB. Thus noise in water at 500 Hz must have a sound pressure level at least 25 dB greater than in air to present the same auditory hazard.

The failure to find a credible dose/response relationship between waterborne sound levels and TTS during the second experiment may be due to the shorter exposure duration and/or the manner in which baseline audiograms were determined.

From the results shown, it is apparent that exposure in water to the conditions of these experiments is not hazardous to divers' hearing. Most trials were followed by comments from the subject to the effect that the sound

was faint; only at the higher exposure levels at some frequencies did they describe the signal as "beginning to get loud". Further evidence of the innocuous nature of the in-water exposure levels used here is that the subjects complained about in-air exposure levels as being loud and unpleasant. Few such complaints were made about the waterborne signals.

However, the lack of consistently measurable TTS limits the utility of these results. The present results do not provide a test for the equal sensory magnitude hypothesis and, more to the point, they do not permit derivation of hearing conservation rules for exposure to underwater sound.

The results for the 15-minute exposures to 500 Hz indicate that this research was on the correct path. Initial exposure levels should have been considerably higher than those used in the present experiments. The initial exposure levels proposed by Smith et al. (1988) would have produced more useful results.

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141 to 161 dB. The maximum TTS observed in any subject was 15.5 dB for any 15 minute exposure condition. For the second group, mean TTS was never as high as 10 dB for any exposure condition and no credible dose/response relationship was apparent. It was concluded that bareheaded SCUBA divers may be exposed continuously for fifteen minutes to warble tones centered at 2000 Hz through 3000 Hz at sound pressure levels as high as 161 dB re 1 μ Pa, and to warble tones centered at 4000 Hz through 6000 Hz at sound pressure levels as high as 171 dB re 1 μ Pa without hazard to hearing. Bareheaded SCUBA divers may be exposed for four minutes to warble tones (125 Hz through 1000 Hz) at sound pressure levels as high as 161 dB re 1 μ Pa without hazard to hearing. Longer exposures at these frequencies and levels may not be innocuous. However, fifteen minute exposures to 500 and 1000 Hz warble tones are not hazardous to ears at 151 dB re 1 μ Pa. The warble tones used here are comparable to 1/3 octave bands of noise or frequency sweeps of the same extent (e.g. some sonar transmissions). Because initial exposure levels were low, insufficient time was available to create conditions in which measurable TTS could be induced with most in-water exposures. Some results indicate that at 500 Hz, noise exposure levels in water may be about 25 dB higher than permissible exposure levels in air.